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# Detailed Study of Emergency Diesel Generator Performance Using EPIX/RADS Database

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# DETAILED STUDY OF EMERGENCY DIESEL GENERATOR PERFORMANCE USING EPIX/RADS DATABASE

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## ABSTRACT

A recent report was published by the U.S. Nuclear Regulatory Commission – *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants*, NUREG/CR-6928. That report characterized industry performance (generally covering 1998 – 2002) for 51 component types found in commercial nuclear power plants. For example, for emergency diesel generators, three failure modes were identified: fail to start and reach rated speed and voltage, fail to load and run for one hour, and fail to run beyond one hour. Data from the U.S. industry contained in the Equipment Performance and Information Exchange (EPIX) database maintained by the Institute for Nuclear Power Operations were used to evaluate the failure probabilities and rates for these failure modes, covering 1998 – 2002. The software package Reliability and Availability Database System (RADS) was used to search and process the EPIX data. In addition, train test and maintenance unavailability was characterized for 34 train types.

As a follow-on effort to this report, several components will be analyzed in more detail each year. These detailed studies include more recent data and analyze various subcategories such as manufacturer, system, size and type (as applicable). In addition, engineering insights such as piece part contribution to each failure mode and failure cause will be determined. This paper summarizes the preliminary results for emergency diesel generators. EPIX data coverage was expanded to include 1998 – 2007 and reliability results were compared with unplanned demand performance (bus under voltage events requiring the emergency diesel generator to start, load and run) over the same period. In addition, performance by manufacturer was evaluated. Finally, piece part contributions and failure causes were determined for each failure mode.

*Key Words*: component reliability, emergency diesel generator, train unavailability

# 1 INTRODUCTION

A recent report was published by the U.S. Nuclear Regulatory Commission (NRC) – *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants*, NUREG/CR-6928 [1]. That report characterized industry performance (generally covering 1998 – 2002) for 51 component types found in commercial nuclear power plants. Data from the U.S. industry contained in the Equipment Performance and Information Exchange (EPIX) database [2] maintained by The Institute for Nuclear Power Operations were used to evaluate the failure probabilities and rates for applicable failure modes, covering 1998 – 2002. The software package Reliability and Availability Database System (RADS) [3] was used to search and process the EPIX data. In addition, train test and maintenance unavailability was characterized for 34 train types.

As a follow-on effort to this report, several components will be analyzed in more detail each year. The purposes of these more detailed studies are the following:

- Compare 1998 – 2002 performance with more recent data (2003 – 2007)
- Compare EPIX data results (containing mostly test data) with unplanned demand performance over the same period
- Generate new baselines using 1998 – 2007 data (if appropriate)
- Identify important differences in performance within component subcategories such as system, manufacturer, size, type, and environment (as applicable)
- Identify piece part contributions to and failure cause for each failure mode

This paper summarizes the preliminary results of the detailed study of emergency diesel generators (EDGs).

# 2 EDG COMPONENT BOUNDARY

As defined in the Mitigating Systems Performance Index (MSPI) Program [4], the EDG component boundary includes the diesel engine with all components in the exhaust path, electrical generator, generator exciter, output breaker, combustion air, lube oil systems, fuel oil system (local), starting compressed air system, and local instrumentation and control circuitry. The sequencer, room heating and ventilation, fuel system (extended), and service water system cooling (except for control of flow to heat exchanger) are excluded. Note that this differs from the definition used for the common-cause failure (CCF) database [5], where the sequencer is included within the EDG component boundary. Also, the NRC system study for EDGs [6] included the sequencer and room heating and ventilation.

# 3 FAILURE MODES AND DATA COLLECTION

The EDG failure modes include fail to start (FTS), fail to load and run for one hour (FTLR), and fail to run beyond one hour (FTR>1H). These failure modes were used in NUREG/CR-6928 and are similar to those used in the MSPI Program. There is some uncertainty concerning when the run hours should start to be counted; should they start as soon as the EDG starts or should they start only after the output circuit breaker has closed? For this study, the run hours start as soon as the EDG is started, which is the way data have been reported in EPIX.

Guidelines for determining whether a component event reported in EPIX is to be included in FTS, FTLR, or FTR>1H are similar to those used in the MSPI Program. In general, any circumstance in which the component is not able to meet the performance requirements defined in the probabilistic risk assessment (PRA) is counted. This includes conditions revealed through testing, operational demands, unplanned demands, or discovery. Also, run failures that occur beyond the typical 24-hour mission time in PRAs are included. However, certain events are excluded: slow engine starting times that do not exceed the PRA success criteria, conditions that are annunciated immediately in the control room without a demand, and run events that are shown to not have caused an actual run failure within 24 hours. Also, events occurring during maintenance or post-maintenance testing that are related to the actual maintenance activities are excluded. Finally, in contrast to the MSPI Program, a general guideline on slow starting times is to include only those slow starts requiring more than 20 seconds as FTS events, similar to what was done for the CCF database and the EDG system study. (In the MSPI Program, most licensees chose to use technical specification requirements for fast starts as their success criteria – typically less than 10 seconds to start.) All of the EDG events within EPIX were reviewed to ensure that they were binned to the correct failure mode – FTS, FTLR, FTR>1H, or no failure. However, even given detailed descriptions of failure events, this binning still required some judgment and involves some uncertainty.

Guidelines for counting demands and run hours are similar to those in the MSPI Program. Start and load/run demands include those resulting from tests, operational demands, and unplanned demands. Demands during maintenance and post-maintenance testing are excluded. Similarly, run hours include those from tests, operational demands, and unplanned demands. Note that the test demands and run hours dominate the totals, compared with operational and unplanned demands and run hours.

## 4 NUREG/CR-6928 BASELINE PERFORMANCE FOR EDGS

NUREG/CR-6928 provides the most recent estimates for U.S. commercial nuclear power plant EDG unreliability. That document analyzed EPIX data (processed by RADS) over 1998 – 2002 to determine industry-average performance – component unreliability (UR) and train unavailability (UA) – centered about the year 2000. Table I summarizes the UR and UA data and resulting failure probability and rate distributions. FTS and FTLR are characterized by beta distributions, while FTR uses a gamma distribution. The resulting mean values for FTS, FTLR, and FTR>1H indicate improved performance compared with older historical estimates.

**Table I. EDG industry-average component UR and train UA from NUREG/CR-6928**

| Failure Mode | Events | Demands or Hours | Mean (MLE) (note a) | Mean (EB) (note b) | Units | Distribution |
|---|---|---|---|---|---|---|
| FTS | 98 | 24206 | 4.05E-03 | 4.53E-03 | 1/d | Beta (1.075, 236.2) |
| FTLR | 61 | 21342 | 2.86E-03 | 2.90E-03 | 1/d | Beta (1.411, 486.6) |
| FTR>1H | 50 | 59875 | 8.35E-04 | 8.48E-04 | 1/h | Gamma (2.010, 2370 h) |
| Train UA | NA | NA | 1.34E-02 | NA | 1/d | Beta (3.586, 264.0) |

a. Maximum likelihood estimate (MLE) = events/demands or hours

b. Parametric empirical Bayes estimate, assuming variable performance between plants [7]

Also presented in Table I is the NUREG/CR-6928 estimate for EDG train UA resulting from test and maintenance outages while the plant is in critical operation. That estimate represents an average of 219 EDG trains, using MSPI basis document UA data covering 2002 – 2004. The mean UA of 1.34E-2 represents an increase compared with Reactor Oversight Process Safety System Unavailability (ROP SSU) [8] results over 1998 – 2002 (approximately 9.0E-3, with fault exposure hours removed). This increase is due to both increased online maintenance in recent years and differences in reporting guidelines. For example, the ROP SSU did not include EDG overhauls performed while the plant is in critical operation, while the MSPI does include this type of outage.

## 5 EDG UPDATE RESULTS USING 1998 – 2007 DATA

NUREG/CR-6928 EDG component UR and train UA estimates are based on EPIX data for 1998 – 2002 (and EDG train UA data for 2002 – 2004). In contrast, this EDG study expands the data to include 2003 through 2007. This doubles the data collection period. Trend plots for FTS, FTLR, and FTR>1H are presented in Figures 1 through 3, covering 1998 – 2007. Estimates for each year are Bayesian updates of a constrained noninformative prior using only data for that year. The downward trend for FTS is not significant (p-value of 0.075), using 0.05 as the value for significance. Also, the upward trends for FTLR and FTR>1H are not significant (p-values of 0.32 and 0.43, respectively).

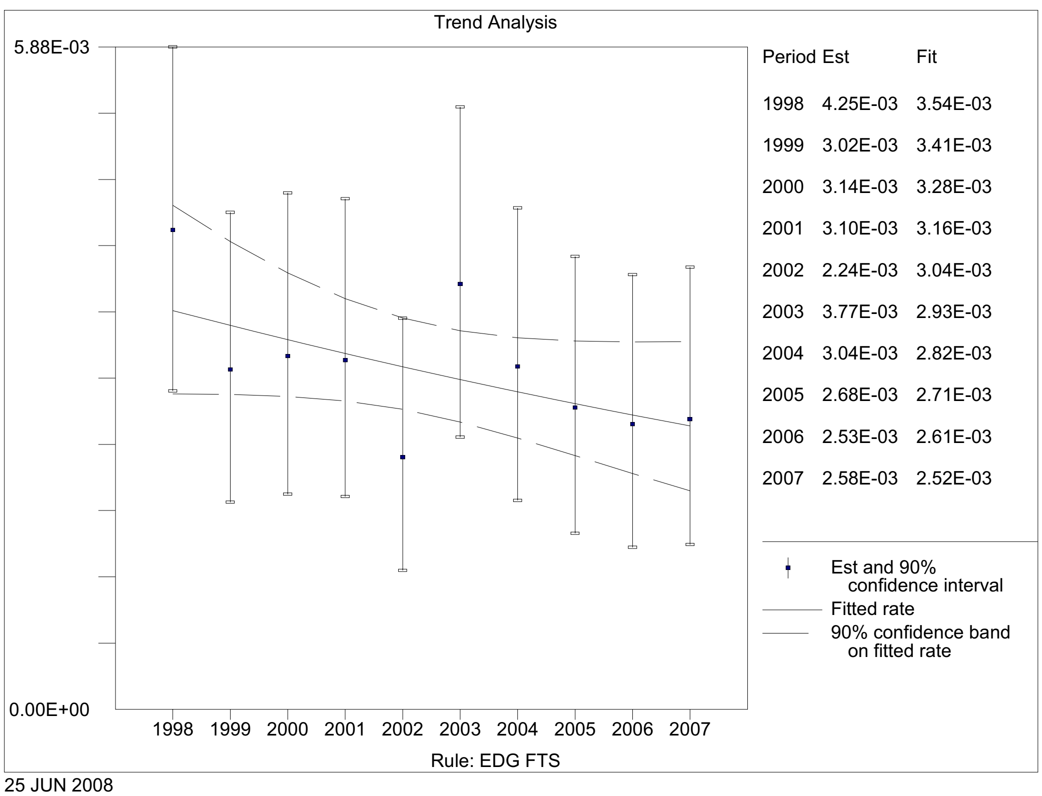


**Figure 1. EDG FTS trend plot (1998 – 2007)**

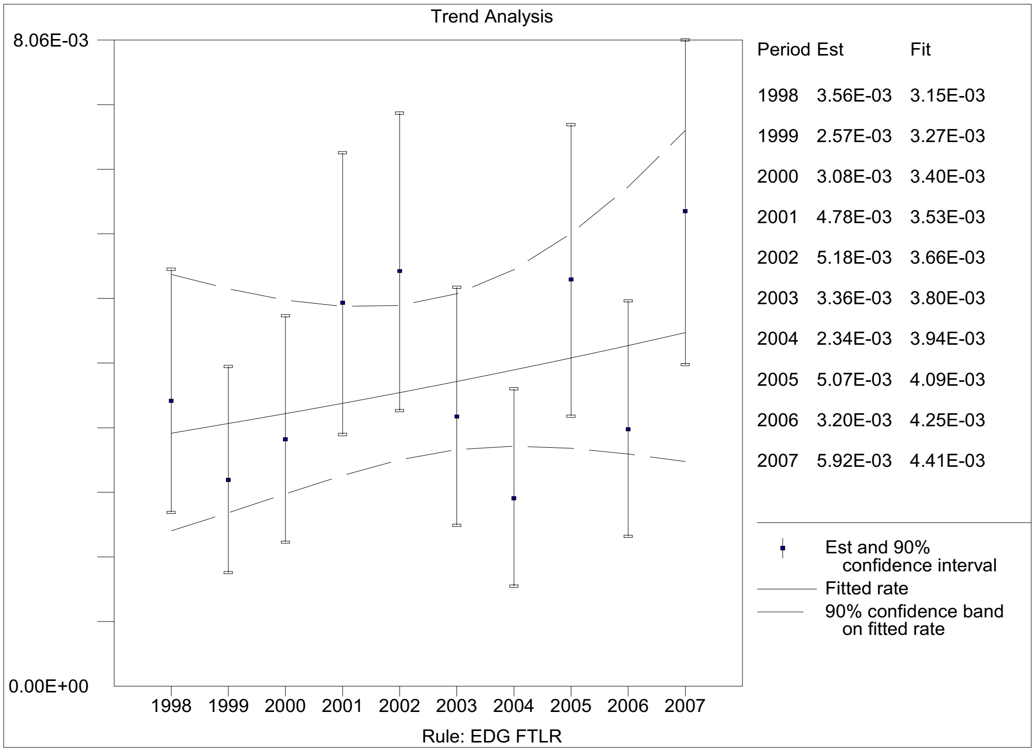


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**Figure 2. EDG FTLR trend plot (1998 – 2007)**

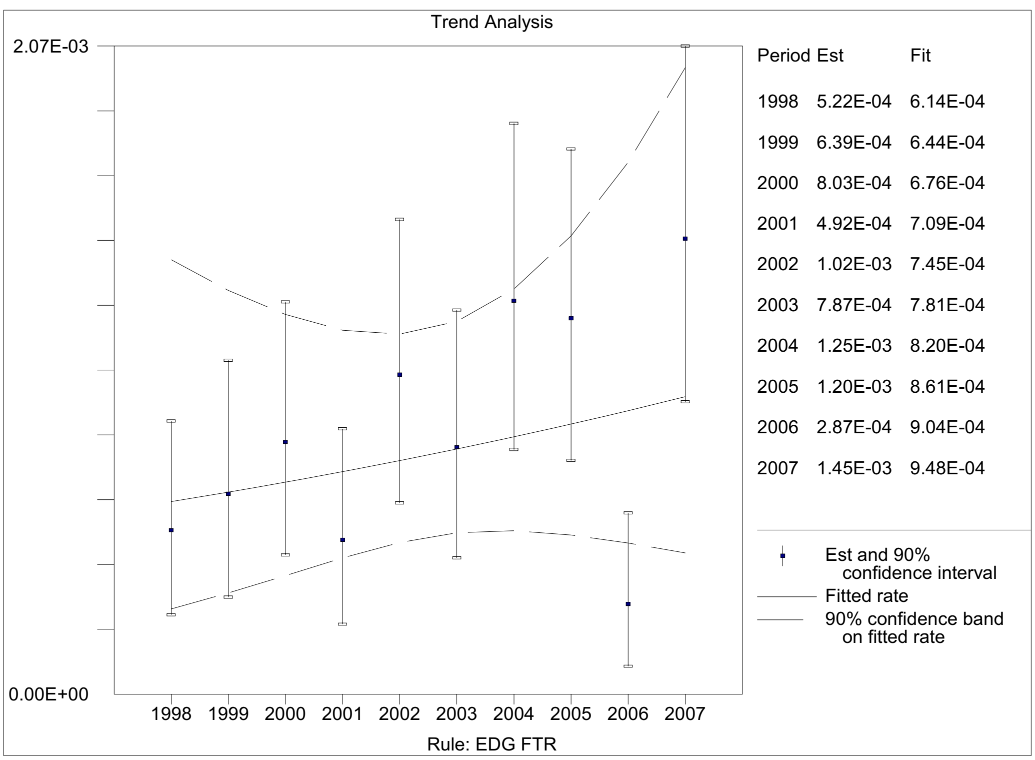


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**Figure 3. EDG FTR>1H trend plot (1998 – 2007)**

The trend plot for EDG train UA is presented in Figure 4. This plot includes ROP SSU data for 1998 – 2002 and MSPI train UA data for 2002 – 2007. (Data for 2002 include a mix of the two because not all of the plants reported MSPI train UA data for 2002.) There is a step increase in the train UA around 2002, which is the result of switching from one database to another, with each having differing reporting guidelines. Therefore, a trend line is not presented. A major reason for the jump is believed to be the inclusion of EDG overhaul hours in the MSPI data (if performed during critical operation). However, some of the jump is believed to be the result of increased maintenance other than overhauls during critical operation.

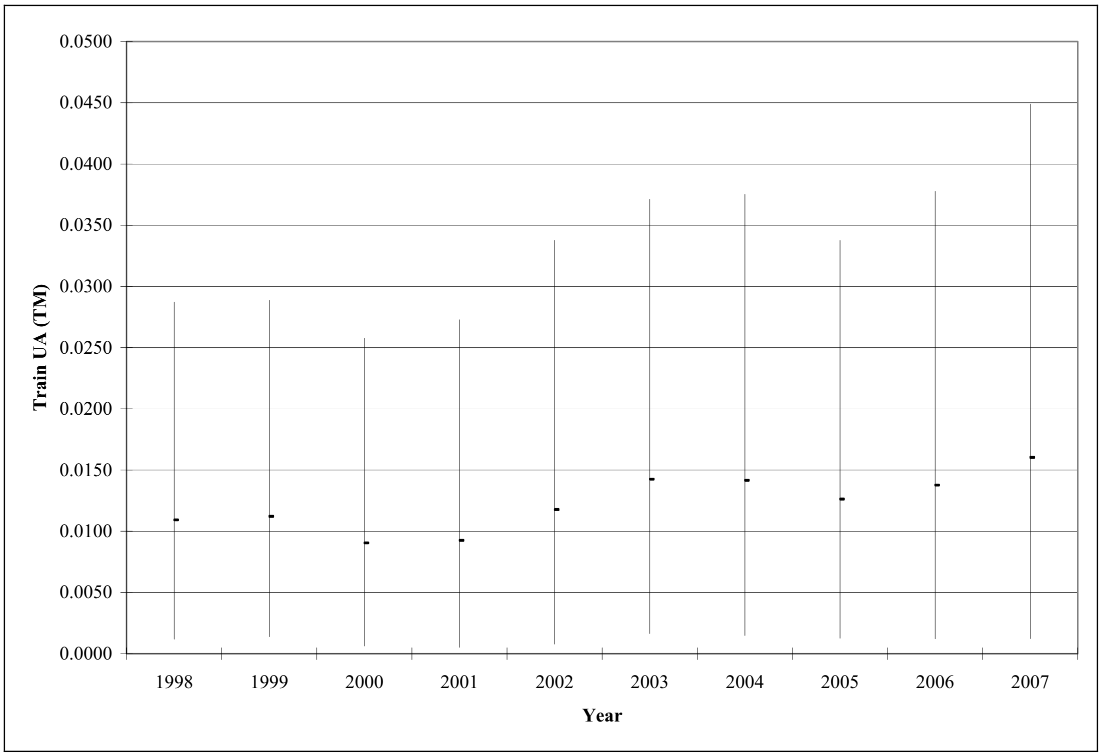


**Figure 4. EDG train UA trend plot (1998 – 2007)**

EDG industry-average performance using the entire 1998 – 2007 period is summarized in Table II. Results are compared with the NUREG/CR-6928 results using 1998 – 2002 data in the table. The new FTS mean of 3.12E-3/d is lower than the NUREG/CR-6928 mean of 4.53E-3/d. However, the new FTLR mean is 4.06E-3/d, compared with 2.90E-3 from NUREG/CR-6928. The reasons for these changes are not clearly known yet; however, they may be just the result of some recategorization of EDG failure events (moving FTS events into FTLR). FTR results are similar for both data periods.

Table II includes an additional row for FTR>1H results in which the first hour of EDG operation has been removed. The MSPI Program includes this first hour of operation is its FTR calculations. NUREG/CR-6928 also included this first hour of operation in its FTR>1H calculations (based on the mistaken assumption that the EPIX EDG run hours had excluded this first hour of operation). The most appropriate approach for estimating FTR>1H rates is to exclude this first hour of operation. The final version of this detailed EDG study will recommend that this approach be used, along with its associated results.

**Table II. EDG industry-average performance using data from 1998 – 2007**

| Failure Mode | Events | Demands or Hours | Mean (MLE) (note a) | Mean (EB) (note b) | Units | Distribution | NUREG/ CR-6928 Mean (EB) 1998 - 2002 Data |
|---|---|---|---|---|---|---|---|
| FTS | 137 | 45231 | 3.03E-03 | 3.12E-03 | 1/d | Beta (3.508, 1122) | 4.53E-03 |
| FTLR | 154 | 38947 | 3.95E-03 | 4.06E-03 | 1/d | Beta (2.413, 591.8) | 2.90E-03 |
| FTR>1H | 104 | 123296 | 8.43E-04 | 8.41E-04 | 1/h | Gamma (13.10, 15570 h) | 8.48E-04 |
| FTR>1H (note c) | 104 | 78065 | 1.33E-03 | Unknown at this time | 1/h | Gamma (10, 7519 h) | 1.40E-03 |
| Train UA | NA | NA | 1.42E-02 | NA | 1/d | Beta (2.600, 180.5) | 1.34E-02 |

a. Maximum likelihood estimate (MLE) = events/demands or hours

b. Empirical Bayes estimate, assuming variable performance between plants

c. FTR>1H results after removing first hour of operation per demand. These results are MLEs because the RADS software has not yet been modified to correct the run hours. The alpha parameter for the gamma distribution is a guess at this time.

## 6 COMPARISON OF EPIX RESULTS WITH UNPLANNED DEMANDS

Because the EPIX EDG data are dominated by test demands (over 95% of the demands are typically from tests), an ongoing concern is whether these mostly test data adequately represent EDG performance during unplanned demands. To answer this question, licensee event reports (LERs) were reviewed to identify actual unplanned EDG demands involving bus under voltage conditions. Such events require the associated EDG to start, load onto the bus and power the bus until normal power is recovered to the bus. There are additional EDG unplanned demands in which a bus under voltage condition did not exist. In those cases, the EDG did not have to load and power the bus. Such unplanned demands do not fully exercise the mission of the EDGs and therefore were not counted.

The EDG unplanned demand data covering 1998 – 2007 are summarized in Table III. Unlike the EPIX data over the same period (45231 demands), there were only 223 unplanned demands associated with bus under voltage conditions. (The average EDG run time per unplanned demand is 8.6 h, including the first hour of operation.) In addition, compared with 395 EPIX EDG failures, there were only nine failures from unplanned demands. Of these nine, four were quickly and easily recovered such that they could load and power the bus. Comparisons in Table III include cases using the nine failures and the five unrecovered failures. Sequencer results are also presented in the table for completeness, although the sequencer is outside of the EDG component boundary.

Consistency between the unplanned demand data and industry-average performance from EPIX (from Table II) was evaluated using the predictive distribution approach outlined in the *Handbook of Parameter Estimation for Probabilistic Risk Assessment*, NUREG/CR-6823, Sections 6.2.3.5 and 6.3.3.4 [7]. Simulation is required. For FTS, the unplanned demand data were aggregated at the plant level (failures and demands). Assuming each plant can have a different failure probability, the industry-average distribution (from Table II) was sampled for each plant. The predicted number of FTS events for each plant was evaluated using the binomial distribution with the plant-specific failure probability and its associated number of demands.

Then the total number of predicted failures was obtained by summing the individual plant results. This process was repeated 1000 times (Latin hypercube sampling), each time obtaining a total number of predicted failures. The 1000 sample results were ordered from high to low. Then the actual number of unplanned demand failures observed (listed in Table III) was compared with this ordered sample to determine the probability of observing this number of failures or greater. If the probability was greater than 0.05, then the unplanned demand performance was considered to be consistent with the industry-average distribution obtained from the EPIX data analysis.

**Table III. EDG unplanned demand performance comparison with industry-average performance from EPIX data**

| Data Set | Failure Modes | Plants | Demands or Hours | Failures | Expected Failures | Probability of ≥ Failures | Consistent with Industry-Average Performance? |
|---|---|---|---|---|---|---|---|
| Consistency of EDG Unplanned Demand Data (without recovery considered) with Industry-Average Performance | | | | | | | |
| Unplanned Demands | FTS | 73 | 223 | 2 | 0.7 | 0.15 | Yes |
| Unplanned Demands | FTLR | 73 | 223 | 3 | 0.9 | 0.07 | Yes |
| Unplanned Demands | FTR | 73 | 1745.6 h | 4 | 2.3 | 0.20 | Yes |
| Unplanned Demands | FTS, FTLR, and FTR | 73 | 223 and 1745.6 h | 9 | 3.9 | 0.01 | No |
| | | | | | | | |
| Consistency of EDG Unplanned Demand Data (with recovery considered) with Industry-Average Performance | | | | | | | |
| Data Set | Failure Modes | Plants | Demands or Hours | Failures | Expected Failures | Probability of ≥ Failures | Consistent with Industry-Average Performance? |
| Unplanned Demands | FTS | 73 | 223 | 1 | 0.7 | 0.48 | Yes |
| Unplanned Demands | FTLR | 73 | 223 | 2 | 0.9 | 0.22 | Yes |
| Unplanned Demands | FTR | 73 | 1745.6 h | 2 | 2.3 | 0.67 | Yes |
| Unplanned Demands | FTS, FTLR, and FTR | 73 | 223 and 1745.6 h | 5 | 3.9 | 0.33 | Yes |
| | | | | | | | |
| Consistency of Sequencer Unplanned Demand Data with Industry-Average Performance | | | | | | | |
| Data Set | Failure Modes | Plants | Demands | Failures | Expected Failures | Probability of ≥ Failures | Consistent with Industry-Average Performance? |
| Unplanned Demands | FTOP | 73 | 223 | 2 | 0.7 | 0.18 | Yes |
| Unplanned Demands (recovery considered) | FTOP | 73 | 223 | 1 | 0.7 | 0.53 | Yes |

The consistency checks using unplanned demand data without recovery considered indicate that each failure mode (FTS, FTLR, and FTR>1H) is consistent with its industry-average distribution from Table II. However, because each unplanned demand failure total is higher than the expected number of failures, when all three failure modes are combined, the result lies at the

1% portion of the predictive distribution. This indicates a strong inconsistency. However, when recovery is considered, the results for individual failure modes and all three combined are consistent with the results using EPIX data from the same period. Finally, the sequencer unplanned demand performance is consistent with the industry-average distribution in NUREG/CR-6928 with and without recovery considered.

## 7 EDG PERFORMANCE BY MANUFACTURER

Table IV presents the results of the evaluation of EDG performance by manufacturer. EPIX contains information on EDG manufacturers, but it appears that over the years some manufacturers have changed names or have been acquired by other manufacturers. Therefore, in order to identify the original manufacturer, the EPIX information was supplemented by other EDG reports. The results are a consistency check against the industry-average distributions in Table II. The comparison was made for the combination of all three failure modes. Two manufacturers' EDG performances lie in the upper 95% of the predictive distribution (superior performance). Two lie in the lower 5% (degraded performance), but these manufacturers involve very few EDGs, so the data are limited. The rest of the manufacturers lie within the 5% to 95% interval and are consistent with the industry-average performance.

**Table IV. EDG performance by manufacturer**

| EDG Manufacturer Performance Consistency with Industry-Average Performance - FTS, FTLR, and FTR Combined | | | | | | |
|---|---|---|---|---|---|---|
| Manufacturer | Code | EDGs | Actual Failures | Expected Failures | Probability ≥ Actual Failures | Consistent with Industry-Average Performance? (note a) |
| Worthington Corp | WC | 4 | 17 | 7.3 | 0.00 | No |
| SAC/Compair Luchard | SC | 1 | 5 | 1.7 | 0.04 | No |
| TransAmerica DeLaval | TD | 20 | 47 | 40.8 | 0.25 | Yes |
| Nordberg | NB | 8 | 21 | 18.2 | 0.32 | Yes |
| Jeumont Schndr | JS | 2 | 8 | 7.7 | 0.49 | Yes |
| ALCO Power | AP | 24 | 47 | 53.4 | 0.65 | Yes |
| Fairbanks Morse/Colt | FM/C | 65 | 109 | 127.9 | 0.93 | Yes |
| Electro Motive/General Motors | EM/GM | 68 | 95 | 133.1 | 1.00 | Yes |
| Cooper Bessemer | CB | 31 | 46 | 73.0 | 1.00 | Yes |
| Totals | | 223 | 395 | 463.2 | | |
| a. If the probability of observing the actual failures or greater is > 0.05, then the manufacturer performance is considered to be consistent with the industry-average performance. | | | | | | |

## 8 EDG PIECE PART CONTRIBUTION TO FAILURE MODES

EDG piece part contributions to the three failure modes are presented in Figures 5 through 7. The piece parts are similar to those used in the CCF database. For FTS, instrumentation and control and the generator piece parts have the highest percentage contributions to failures. FTLR high contributors include the breaker and instrumentation and control. Finally, FTR high contributors include the cooling, engine, fuel oil, and instrumentation and control.

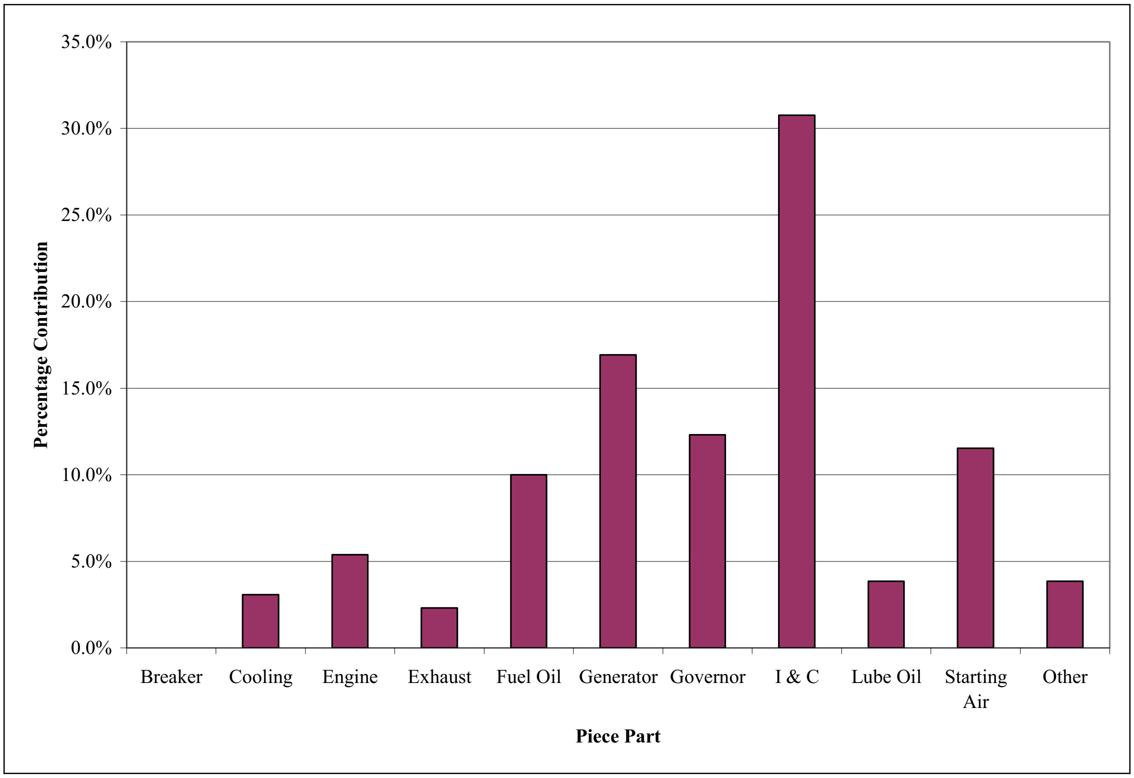


**Figure 5. EDG FTS breakdown by piece part**

## 9 CONCLUSIONS

This paper summarizes preliminary results of a detailed study of EDG component UR and train UA, using EPIX data covering 1998 – 2007. This is an update of results in NUREG/CR-6928, which used EPIX data covering 1998 – 2002. Addition of the newer data and a detailed review of failure events resulted in a lower FTS probability and higher FTLR probability compared with NUREG/CR-6928. The FTR>1H rates and train UA probabilities are similar. However, the FTR>1H rate should be recalculated using only those run hours beyond the first hour of operation.

Comparison of EDG unplanned demand performance obtained from a review of LERs with EPIX results (based mainly on test results) indicates that the unplanned demand performance is consistent with the EPIX results if recovery is considered for the unplanned demands. However, if recovery is not considered, the unplanned demand performance is significantly worse than the EPIX results. (The EPIX data do not consider recovery. All events must be reported, even though some might have been recovered.)

Additional engineering insights include a ranking of EDG manufacturers by component UR and piece part contributions to the FTS, FTLR, and FTR>1H failure modes. This information may be helpful to both NRC inspectors and industry.

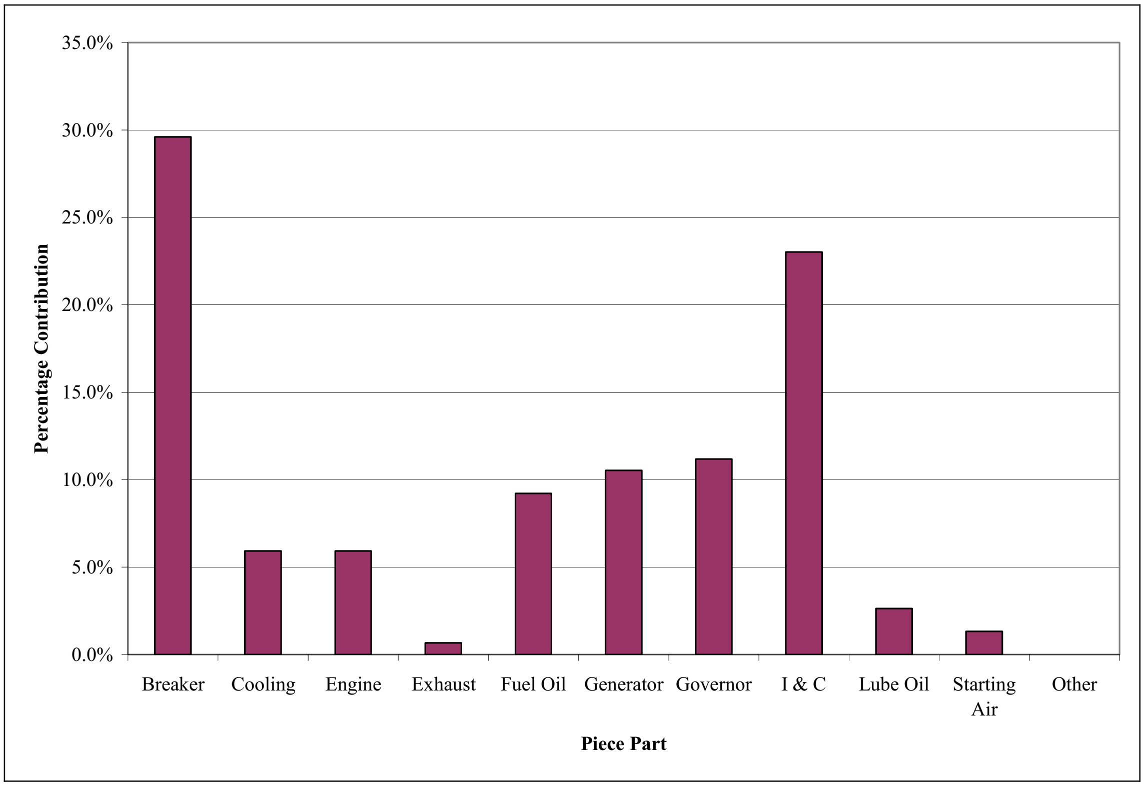


**Figure 6. EDG FTLR breakdown by piece part**

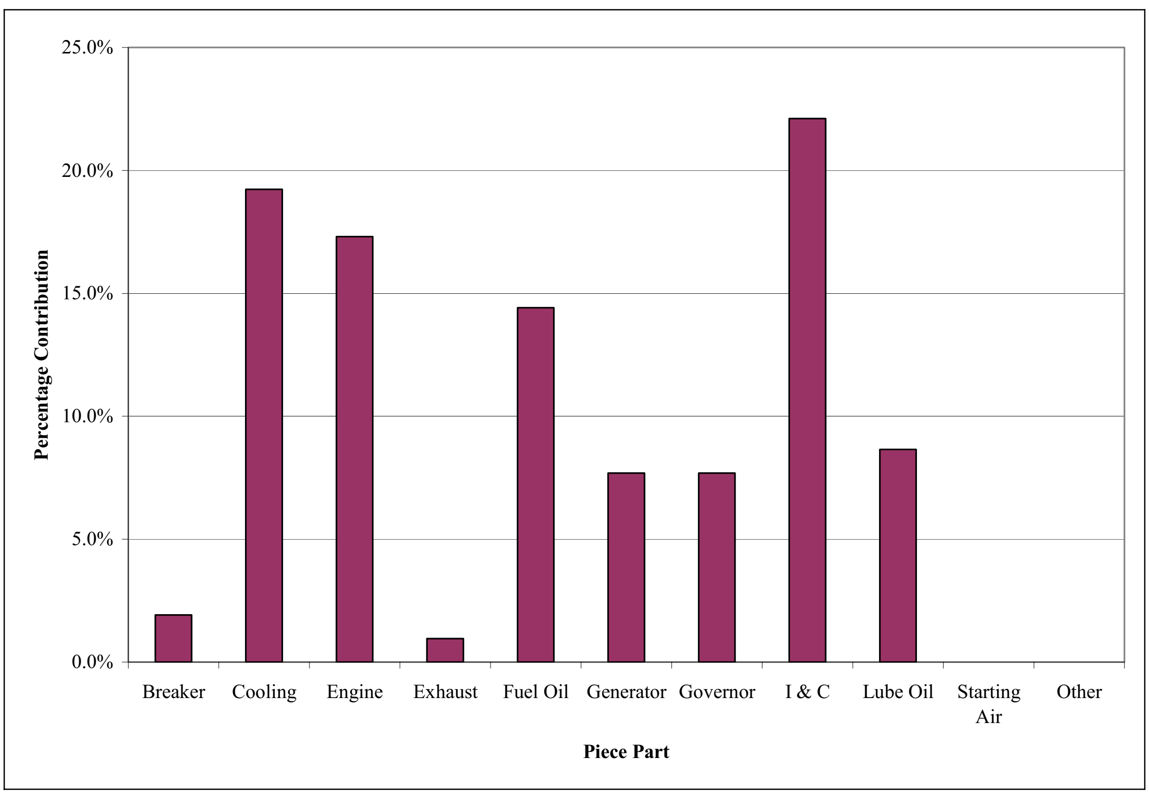


**Figure 7. EDG FTR breakdown by piece part**

## 10 ACKNOWLEDGMENTS

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